Title
Children and Adolescents' Anthropometrics Body Composition from 3-D Optical Surface Scans

Journal
Obesity, 27(11)

ISSN
1930-7381

Authors
Wong, Michael C
Ng, Bennett K
Kennedy, Samantha F
et al.

Publication Date
2019-11-01

DOI
10.1002/oby.22637

Peer reviewed

HHS Public Access

Author manuscript

Obesity (Silver Spring). Author manuscript; available in PMC 2021 February 15.

Published in final edited form as:

Obesity (Silver Spring). 2019 November ; 27(11): 1738–1749. doi:10.1002/oby.22637.

Children and Adolescents' Anthropometrics Body Composition from 3-D Optical Surface Scans

Michael C. Wong[1,2], **Bennett K. Ng**[2], **Samantha F. Kennedy**[3], **Phoenix Hwaung**[3], **En Y. Liu**[2], **Nisa N. Kelly**[2], **Ian S. Pagano**[2], **Andrea K. Garber**[4], **Dominic C. Chow**[5], **Steven B. Heymsfield**[3], **John A. Shepherd**[1,2]

[1]Graduate Program in Human Nutrition, University of Hawai'i Manoa, Honolulu, Hawaii, USA.

[2]Department of Epidemiology, University of Hawai'i Cancer Center, Honolulu, Hawaii, USA

[3]Pennington Biomedical Research Center, Louisiana State University, Baton Rouge, Louisiana, USA

[4]Division of Adolescent & Young Adult Medicine, University of California, San Francisco, California, USA

[5]John A. Burns School of Medicine, University of Hawai'i, Honolulu, Hawaii, USA.

Abstract

Objective: This study aimed to explore the accuracy and precision of three-dimensional optical (3DO) whole-body scanning for automated anthropometry and estimating total and regional body composition.

Methods: Healthy children and adolescents (n = 181, ages 5–17 years) were recruited for the Shape Up! Kids study. Each participant underwent whole-body dual-energy x-ray absorptiometry and 3DO scans; multisite conventional tape measurements served as the anthropometric criterion measure. 3DO body shape was described using automated body circumference, length, and volume measures. 3DO estimates were compared with criterion measures using simple linear regression by the stepwise selection method.

Results: Of the 181 participants, 112 were used for the training set, 49 were used for the test set, and 20 were excluded for technical reasons. 3DO body composition estimates were strongly associated with dual-energy x-ray absorptiometry measures for percent body fat, fat mass, and fat-free mass (R^2: 0.83, 0.96, and 0.98, respectively). 3DO provided reliable measurements of fat mass (coefficient of variation, 3.30; root mean square error [RMSE], 0.53), fat-free mass (coefficient of variation, 1.34; RMSE, 0.53 kg), and percent body fat (RMSE = 1.2%).

Correspondence: John A. Shepherd (johnshep@hawaii.edu).

Author contributions: JAS, SBH, BKN, SFK, PH, and MCW designed and conducted the research; EYL, NNK, SFK, PH, and MCW were responsible for coordinating the study, meeting with participants, and collecting data; JAS, ISP, MCW, and BKN analyzed the data; all authors contributed to the text of the manuscript; MCW and JAS drafted the manuscript and had primary responsibility over the final content. All authors reviewed and approved the final manuscript.

Disclosure: All authors reported no conflict of interest.

Clinical trial registration: ClinicalTrials.gov identifier NCT03706612.

Conclusions: 3DO surface scanning provides accurate and precise anthropometric and body composition estimates in children and adolescents with high precision. 3DO is a safe, accessible, and practical method for evaluating body shape and composition in research and clinical settings.

Introduction

Evaluating body composition in children and adolescents is a useful component of weight control and exercise programs (1,2). The information gathered from these body composition assessments can be used by health care workers to refine their lifestyle recommendations. This guidance during childhood can, over the long term, help to prevent cardiovascular and metabolic diseases later in life (3).

In a recent study using data from the National Health and Nutrition Examination Survey (NHANES), Skinner et al. (4) reported that 24.8% of girls and 26.2% of boys aged 2 to 19 years in the United States have obesity. Their findings also showed that girls and boys have had a 5.3% and 6.4% respective increase in the prevalence of obesity since 2000. Lifshitz estimated that 75% to 80% of adolescents with obesity will maintain or increase their level of obesity in adulthood (5). Rising rates of obesity in children have been accompanied by increasing rates of metabolic syndrome (6). Despite these prominent associations, little is known about how excess weight relates to body composition measures such as fat mass (FM) in children outside of population-level estimates.

Detecting excess adiposity at a young age is critical for preventing obesity and its many consequences later in life. In a recent longitudinal study of children aged 6 to 18 years, Loeffler-Wirth et al. (7) reported that over 4 years only 3% of children with normal weight and underweight arrived at overweight status, and only 2% of children with overweight arrived at a normal weight. These findings suggest that children with overweight or obesity will likely stay that way as they reach adulthood. This underscores the importance of metabolic health interventions at a young age.

Body composition in research settings is usually evaluated with widely available technologies such as dual-energy x-ray absorptiometry (DXA). FM, lean soft tissue mass, and bone mineral content are derived with DXA systems, which also makes DXA a useful tool in clinical settings to look at body composition and bone density. Din et al. (8) described percent body fat (%BF) in 59 children using DXA and found that regional body composition measurements of FM and fat-free mass (FFM) were better predictors of %BF than BMI and age alone ($\beta = 0.42$, $P < 0.0001$, $R^2 = 0.79$, root mean square error [RMSE] = 1.54). DXA has been broadly used in the age range of 5 to 17 years old. Extensive reference data are available from large NIH studies such as the Bone Mineral Density in Childhood Study (9) and the Centers for Disease Control and Prevention's study that used whole-body DXA scans on 7- to 17-year-old children (10). DXA also has been shown to be precise and reproducible in this age range (11). However, some limitations of DXA are that it is costly and is accompanied by ionizing radiation, thus making it unattractive for clinical use.

Three-dimensional optical (3DO) whole-body surface scanning recently emerged as a versatile and promising tool for body composition and health assessment. 3DO scanners

generate surface renderings, and instrument software automatically generates circumference and length measurements across the whole body. Using these automated measurements, body composition equations for adults were derived and validated (12). Each scan takes less than 1 minute, and hundreds of anthropometric measurements are derived that would otherwise be time-consuming to acquire using manual techniques. In addition, 3DO anthropometry measurements are not influenced by the previous measurement, whereas human technicians may be biased by aiming for their previous reading. Evaluations are low cost and free of ionizing radiation. Our objective was to examine the precision and accuracy of 3DO for anthropometric and body composition measurements in children compared with DXA, tape anthropometric measurements, and estimation equations for Dubois-estimated body surface area.

Methods

Shape Up! Kids (NIH R01 DK111698) is a cross-sectional study of healthy children and adolescents (aged 5–17) stratified by sex, age, ethnicity, and BMI *z* score. The study was designed to investigate the associations between body shape and composition with a variety of health indices. All participants gave informed consent, and the study protocol was approved by the Institutional Review Board (IRB) at Pennington Biomedical Research Center (PBRC; IRB study #2017–10, Federalwide Assurance #00006218); University of California, San Francisco (UCSF; IRB #16–20197); and University of Hawaii Office of Research Compliance (UH ORC; Center of Health Sciences #24282).

Participants

Participants ($n = 181$) were recruited at PBRC, University of Hawaii Cancer Center (UHCC), and UCSF. Exclusion criteria included pregnancy, missing limbs, presence of significant nonremovable metal in the body (e.g., hip replacements), history of body-altering surgery (e.g., breast implants), or hair that could not be contained within a swim cap. Participants were all volunteers and recruited by flyers, news broadcasts, health fairs, and word of mouth. Pretesting preparations included fasting with no food for at least 8 hours (water was allowed during fasting) and no exercise for 24 hours. Each participant's evaluation included height and weight measurements, one DXA scan, duplicate 3DO scans, and tape anthropometric measurements of circumference (waist, hip, biceps, and thighs). Obesity was categorized by BMI *z* score (obesity ≥ 95th percentile) (13).

Tape anthropometric measurements

Following the standard protocol from NHANES, flexible measuring tapes were used to collect waist, hip, arm, and thigh circumferences. Measurements were recorded in triplicate to the nearest 0.1 cm; results were averaged. Waist circumference measurements were taken using marks placed on the top of the iliac crest as reference while the participant stood up straight with their arms crossed. Participants remained in the same position for hip circumference measurements, which were made at the most protruding part of the buttocks. Arm circumference measurements were taken at the midpoint of the acromion process and olecranon while the participant stood with their arm relaxed and hanging loosely. Thigh circumference measurements were taken at the midpoint of the participant's anterior

superior iliac spine and the top of the patella while the participant stood with the corresponding leg positioned forward and slightly bent at the knee (14).

3DO surface scans

Duplicate 3DO surface scans were taken with Fit3D ProScanner version 4.x (Fit3D Inc., San Mateo, California) using a standardized positioning protocol. Participants changed into form-fitting shorts, a sports bra if female, and a swim cap. The ProScanner consists of a rotating platform, a plate for weight measurement, and three infrared cameras on a tower. Participants grasped telescoping handles on the scanner platform and stood up straight with their shoulders relaxed. The platform rotates once around during a full-body scan that takes approximately 45 seconds. Although only 11 circumferences (chest, waist, and hip and left and right biceps, forearm, thigh, and calf) are reported to consumers, approximately 349 measurements from the neck down to the wrist and ankles are automatically derived and available from the manufacturer. The head, hands, and feet are excluded from volume measures. The duplicate scans with repositioning between scans and spaced no more than 15 minutes apart were acquired to quantify test-retest repeatability. Repeatability as defined is also known as short-term reproducibility (15). The Fit3D system is not portable per se but with minimal breakdown, it can be transported and reassembled in a new location.

DXA

Participants completed one whole-body DXA scan on a Hologic Discovery/A or Horizon/A system (Hologic Inc., Marlborough, Massachusetts). DXA scans were all centrally analyzed at UHCC by a trained technologist using Hologic Apex version 5.6 with the (NHANES) Body Composition Analysis calibration option disabled. Participants were scanned in form-fitting clothing without shoes. A certified technician centered the participant on the table with arms at their side, hands pronated, and feet in a plantar flexed position, in accordance with the manufacturer's standard protocol (16). The duration of the scan was approximately 3 minutes. The output from the DXA scan included regional and whole-body %BF, FM, lean soft tissue mass, bone mineral content and density, subcutaneous adipose tissue (SAT), and visceral adipose tissue (VAT). DXA VAT was our criterion to estimate VAT from 3DO anthropometry. Hologic Apex software estimates VAT and SAT from total abdominal fat volume, such that VAT = Total Abdominal Fat − SAT, and SAT is estimated from manufacturer-specific models using the fat projected outside the abdominal walls. DXA VAT has been validated against either magnetic resonance imaging or computed tomography in both adults (17) and children (18). DXA cross-calibration phantoms were circulated between all sites and calibration equations derived to remove systematic bias in all bone and soft tissue results.

Statistical methods

Our goal was to quantify the precision and accuracy of 3DO body composition estimates using DXA results as a standard reference. The complete data set was split into a training and test set. The test set was used to validate the derived body composition equations. The training set included all participants recruited before October 17, 2019. The test set included all participants recruited after October 17, 2019. A *t* test was used to determine any differences between the training and test set. Univariate linear regression analysis was used

to test the agreement of 3DO-estimated hip, waist, bicep, and thigh circumferences against the respective tape anthropometric measurements, 3DO-estimated body surface area against the DuBois model (19), and 3DO-estimated whole-body, trunk, arm, and leg volume measurements against the respective DXA-estimated volumes. 3DO volumes are reported from the maker of the 3DO device. DXA is considered a criterion measure for volume from previous work (16). The validity of 3DO volumes was compared to DXA volumes for those interested in using 3DO volumes. Bland-Altman plots were generated to see the differences between 3DO and DXA. Studentized residual and leverage plots were used to identify outliers (not shown).

A *t* test was used to determine significant differences in measurements by different measurement methods. $P \leq 0.05$ was considered statistically significant. The RMSE and coefficient of variation (%CV) were calculated to quantify precision of 3DO scanner measurements. The coefficients of determination (R^2) reported in this study were adjusted for multiple variables. Models were chosen using the SAS GLMSELECT procedure (version 9.4, SAS Institute, Cary, North Carolina). The stepwise multiple regression method with the Schwarz Bayesian information criterion determined the order of variable entry and exit. The dependent variables were the body composition estimates from DXA, while the 3DO auto-anthropometry were our independent variables.

After finding FM using stepwise multiple regression, FFM was found by subtracting FM from total mass. Fat mass index (FMI) and fat-free mass index (FFMI) were calculated by dividing FM and FFM by height squared, respectively. The predicted residual sum of squares (PRESS) was used to stop the variable selection process. Fivefold cross-validation partitioned the data into five subsets, used four subsets for training, and omitted one subset for validation. PRESS was computed on all subsets and added. The variable selection process ended when PRESS was minimized. %CV was calculated for each participant to compare the precision among the population. 3DO-estimated volumes were compared against DXA regional and whole-body volumes equations reported by Wilson et al. (16). In comparative analysis, points outside the 95% confidence interval were identified and studied to examine reasons for disagreement between DXA and 3DO body composition estimates. SAS version 9.4 (SAS Institute, Cary, North Carolina) was used for all statistical analyses.

Results

Participants

After exclusions, 112 participants (46 males, 66 females) were included in the present analysis, and 49 participants were included in the validation analysis. From PBRC, 43 non-Hispanic black, 72 non-Hispanic white, and 2 Hispanic participants were recruited. From UCSF, 5 Asian, 4 non-Hispanic black, 4 non-Hispanic white, and 2 Hispanic participants were recruited. From UHCC, 9 Asian, 4 non-Hispanic black, 2 Hispanic, 4 non-Hispanic white, and 10 Native Hawaiian Other Pacific Islander participants were recruited. Eight participants were excluded because the scan data were lost during the processing transfer to Fit3D, two for artifacts, five for excessive movement, and five for not wearing form-fitting clothing. Summary characteristics of the study sample are provided in Table 1. Figure 1 contains a photo of the Fit3D device, a Fit3D scan, the participant's corresponding DXA

scan, and an example image of the automated anthropometry on the mesh. The excluded participants had no statistically significant differences in their demographic and clinical characteristics (e.g., age, height, weight, BMI) compared with those who were fully evaluated and included in the reported analyses (all $P > 0.33$). For the training and test set, there were no statistically significant differences in clinical characteristics (e.g., age, height, weight, BMI) between the training and validation test sets (all $P > 0.36$).

Precision

Test-retest precision metrics for each measurement are shown in Table 2. The measurements with the best precision were the total lean soft tissue mass, FFMI, and trunk lean soft tissue mass (%CV: 1.85, 1.89, and 2.05, respectively). Children who were younger in age ($P = 0.001$) and taller in height ($P < 0.0001$) had higher precision error in total FM and FFM.

Body composition

The derived body composition equations for total lean soft tissue mass, total %BF, FMI, FFMI, and visceral fat are shown in Table 3. Regional lean soft tissue and FM are also shown with their parameters in Table 3. There were strong associations for total fat and FFM, %BF, FMI, FFMI, and VAT measurements relative to DXA (R^2: 0.96, 0.98, 0.83, 0.96, 0.91, and 0.92, respectively).

Linear regression and Bland-Altman plots are shown in Figure 2 for 3DO measurements against anthropometric tape measurements and DuBois-estimated body surface area. There were strong associations for 3DO waist circumference and hip circumference versus tape anthropometry, as well as surface area measured by 3DO versus DuBois-estimated body surface area (R^2: 0.94, 0.99, and 0.94, respectively). Points labeled 1 and 2 were outliers beyond the 95% confidence interval and had high leverage on their respective plots. High leverage points are defined as points with a greater influence on the slope of the line of best fit.

Figure 3 shows 3DO-estimated volume measurements plotted against DXA-estimated volumes and Bland-Altman plots for whole body, trunk, legs, and arms, respectively. There was also a strong association for 3DO total-body volume, trunk volume, and arm volume relative to DXA (R^2: 0.99, 0.97, and 0.97, respectively), but the Bland-Altman plots showed a size-related bias. The linear regression analysis of the 3DO leg volume versus DXA-estimated leg volume had a lower association, with an R^2 of 0.76. Points labeled 2, 3, and 4 were high leverage outliers on their respective plots. Upon review of these outliers, it was concluded that they did not fall under any of our a priori exclusion criteria. The points of concern were from children who had large circumferences or other reasons that could not be visually interpreted. Figure 4 displays points 1–4 from the previous figures. However, the points of concern in circumference measurements were not outliers in %BF (Figure 4).

Table 4 shows the results from the test set. Total FM, total FFM, FMI, FFMI, and VAT retained strong correlations to DXA (R^2: 0.93, 0.95, 0.90, 0.81, and 0.89, respectively). %BF had a modest correlation in the test set (R^2: 0.70).

Discussion

Estimates of 3DO body composition, volumes, circumferences, and whole-body surface areas were strongly associated with the corresponding DXA measurements, manual anthropometry, and calculated DuBois equation estimates, respectively. These estimates were robust and had precision values similar to the criterion methods. This study is the first to utilize 3DO technology to estimate children's body composition with a focus on clinical applications. Overall, this study supports the use of 3DO as a precise and accurate modality to use for body composition measurements, circumferences, surface areas, and volumes. The 3DO technology is relatively low cost, easy to assemble and operate, does not require physical contact, and can be installed in remote regions that lack the resources to operate more advanced devices such as DXA.

From our study sample, 20 individuals were excluded for their 3DO scan because of our a priori criteria that included disrupted scan artifacts because of movement, visible accessories (e.g., glasses and watches), and improper loose clothing. To mitigate future exclusions, verbal reinforcement of positioning and steadiness on the scanner is necessary. In addition, clinical evaluators need to be sure the participants are in the appropriate form-fitting clothing and not wearing any objects that cause artifacts in the scan.

Body composition predicted by 3DO has been previously reported in adults and shown to be precise for whole-body FM and FFM (RMSE: 0.50 kg and 0.50 kg, respectively) (12). The precision error in our children was almost identical for FM and FFM (RMSE, 0.53 kg and 0.53 kg, respectively). In addition, our association of %BF to DXA was almost identical to that in the adults reported by Ng et al. (R^2: 0.83 and 0.84, respectively). Furthermore, Ng et al. showed that FM and FFM models displayed a strong association to DXA in adults (R^2: 0.95 and 0.96, respectively), which is almost identical to the results from this study (R^2: 0.96 and 0.98, respectively). Other outcome variables derived in our study (circumferences, surface areas, and volumes) were comparable to, if not better than, Ng et al.'s results.

Compared with other established body composition methods, 3DO showed similar results to DXA. Air displacement plethysmography (ADP)-estimated %BF showed a strong correlation with DXA-estimated %BF (R^2: 0.90–0.95) (20,21). Bioelectrical impedance analysis had a %BF correlation closer to 3DO (R^2: 0.79–0.83) compared with DXA (22,23). Although ADP registered a higher correlation to DXA for %BF, 3DO still remains a more accessible method and does not require trained personnel to operate. Another interesting value to examine is RMSE because R^2 can be inflated with range and RMSE can tell us how far the estimate is from the criterion. For FFM, 3DO had a lower RMSE (1.83 kg) than previously shown in bioelectrical impedance analysis (RMSE, 2.70–12.4 kg) (24,25) and ADP (RMSE, 6.6 kg) (26). With the strong correlations and low RMSE for %BF, FM, and FFM from 3DO to DXA, 3DO can substitute as a reasonable alternative method if DXA is not available because of resource or accessibility barriers. 3DO is also a novel approach for evaluating three-dimensional shape that potentially provides information on FM and FFM distribution that other modalities lack.

The high correlation of %BF prediction from 3DO and DXA (R^2: 0.83) supports the use of 3DO devices in a clinical setting to safely estimate body composition in children and adolescents. The Bland-Altman plots generally show larger volume differences when the mean increases. This could be due to potential accuracy issues with larger individuals. However, when looking at the %BF Bland-Altman plot (Figure 4), there was no obvious positive or negative trend, and the scatter was spread evenly. This suggests that there are some systematic biases in Fit3D's volume measurements compared with DXA, but our %BF equation is stable and has great potential.

However, the ability of this technology to monitor body composition changes over time is limited. The RMSE for both total FM and FFM was 0.53 kg, which is higher than DXA in children (~0.18 kg and 0.25 kg, respectively) (27). Therefore, to determine whether two measures are different with 95% confidence, often called the least significant change (LSC), requires a change of 2.77 multiplied by the precision error (28). The LSC for fat or lean soft tissue mass is 2.77 × 0.53 kg = 1.47 kg, whereas for DXA, we would expect an LSC of approximately 1 kg. An approach to reduce the precision error to that of DXA and to track smaller changes of body composition over time would be to take four or more scans and average them because the precision in the estimate improves by the square root of the number of scans (i.e., the average of four scans would lower the precision error from 0.53 kg to 0.27 kg). More longitudinal studies should be done to study other ways to improve the intrinsic precision of the 3DO method.

Other studies have been conducted to validate 3DO accuracy, precision, and clinical applications. Although Wang et al. (29) obtained more precise whole-body volume measurements (%CV, 0.38) using a four-camera laser-triangulation scanner, their scanner was more expensive (~$50,000–$100,000), whereas the Fit3D ProScanner costs less (~$10,000). Wells et al. (30) reported a 0.5-cm precision for body circumferences with a six-camera structured light scanner, similar to the results from the Fit3D, a three-camera light scanner.

The strength of our study lies in the use of multiple body composition modalities in a group of children and adolescents diverse in levels of adiposity and race and ethnicity. We included a wide range of ages from 5 to 17 years and five different racial/ethnic groups (non-Hispanic white, non-Hispanic black, Hispanic, and Asian). The children were either classified as underweight, normal weight, having overweight, or having obesity according to BMI z score.

Our study had several limitations. Young children had a hard time staying still for the 45-second duration of the scan. Our study was carried out in healthy individuals without any known diseases that may alter their shape and body composition such as anorexia, malnutrition, bulimia, or muscle-wasting disorders. Each technologist performing manual anthropometry was trained and validated by staying within 10% of total error from our lead technologists. However, an inter-reader validation was not performed. Further studies are needed to test this technology in children with these conditions that might influence body shape and composition.

Conclusion

We conclude that 3DO whole-body surface scanning is a useful clinical modality for body composition and measurements in clinical settings because it is less expensive than DXA, predicts body composition accurately, does not emit ionizing radiation, and can even be used on a daily basis. 3DO is an accessible option for monitoring health. Although it is more precise, DXA requires trained technicians to operate the device and to analyze the results. The 3DO scanner is simple to use, and the results are sent by email within minutes. Larger follow-up studies need to follow the current investigation to better understand 3DO scan technology across more diverse samples with even larger age ranges and ethnic distributions.

Acknowledgments

We thank all the participants and their parents for graciously giving us their time for this study. We also want to thank Tyler Carter at Fit3D for providing us the 3DO data. The data underlying this study cannot be made publicly available because the data contain patient-identifying information. Data are available from the Shape Up! studies for researchers who meet the criteria for access to confidential data. For details and to request an application, please contact Nisa N. Kelly (nnkelly@hawaii.edu) or visit www.shapeup.shepherdresearchlab.org.

Funding agencies:

All phases of this study were funded by the National Institute of Diabetes and Digestive and Kidney Diseases (NIH R01 DK111698).

References

1. Malina RM. Body composition in athletes: assessment and estimated fatness. Clin Sports Med 2007;26:37–68. [PubMed: 17241914]
2. Verduin WM, Helder RVD, Doodeman HJ, Struijf E, Houdijk APJ. Dexa body composition assessment in 10–11 year healthy children. PLoS One 2016;11:e0165275. doi:10.1371/journal.pone.0165275 [PubMed: 27788168]
3. Johnson MJ, Beattie RM. Making body composition measurement a part of routine care in children. Clin Nutr 2018;37:763–764. [PubMed: 29454500]
4. Skinner AC, Ravanbakht SN, Skelton JA, Perrin EM, Armstrong SC. Prevalence of obesity and severe obesity in US children, 1999–2016. Pediatrics 2018;141:e20173459. doi:10.1542/peds.2017-3459 [PubMed: 29483202]
5. Lifshitz F Obesity in children. J Clin Res Pediatr Endocrinol 2008;1:53–60. [PubMed: 21318065]
6. Al-Hamad D, Raman V. Metabolic syndrome in children and adolescents. Transl Pediatr 2017;6:397–407. [PubMed: 29184820]
7. Loeffler-Wirth H, Vogel M, Kirsten T, et al. Longitudinal anthropometry of children and adolescents using 3D-body scanning. PLoS One 2018;13:e0203628. doi:10.1371/journal.pone.0203628 [PubMed: 30212520]
8. Din N, Fan B, Kazemi L, et al. Validation of body composition measures from forearm and lateral distal femur scans of children [abstract]. J Clin Densitom 2018;21:32.
9. Kalkwarf HJ, Zemel BS, Gilsanz V, et al. The Bone Mineral Density in Childhood Study: bone mineral content and density according to age, sex, and race. J Clin Endocrinol Metab 2007;92:2087–2099. [PubMed: 17311856]
10. Kelly TL, Wilson KE, Heymsfield SB. Dual energy x-ray absorptiometry body composition reference values from NHANES. PLoS One 2009;4:e7038. doi:10.1371/journal.pone.0007038 [PubMed: 19753111]
11. Shepherd JA, Wang L, Fan B, et al. Optimal monitoring time interval between DXA measures in children. J Bone Miner Res 2011;26:2745–2752. [PubMed: 21773995]

12. Ng BK, Hinton BJ, Fan B, Kanaya AM, Shepherd JA. Clinical anthropometrics and body composition from 3D whole-body surface scans. Eur J Clin Nutr 2016;70: 1265–1270. [PubMed: 27329614]
13. Centers for Disease Control and Prevention. Recommended BMI-for-age cutoffs. https://www.cdc.gov/nccdphp/dnpao/growthcharts/training/bmiage/page4.html. Updated May 9, 2014 Accessed May 27, 2019.
14. Centers for Disease Control and Prevention. National Health and Nutrition Examination Survey (NHANES) Anthropometry Procedures Manual. https://wwwn.cdc.gov/nchs/data/nhanes/2017-2018/manuals/2017_Anthropometry_Procedures_Manual.pdf. Published 1 2017.
15. Gluer CC, Blake G, Lu Y, Blunt BA, Jergas M, Genant HK. Accurate assessment of precision errors: how to measure the reproducibility of bone densitometry techniques. Osteoporos Int 1995;5:262–270. [PubMed: 7492865]
16. Wilson JP, Mulligan K, Fan B, et al. Dual-energy X-ray absorptiometry-based body volume measurement for 4-compartment body composition. Am J Clin Nutr 2012;95: 25–31. [PubMed: 22134952]
17. Micklesfield LK, Goedecke JH, Punyanitya M, Wilson KE, Kelly TL. Dual-energy X-ray performs as well as clinical computed tomography for the measurement of visceral fat. Obesity (Silver Spring) 2012;20:1109–1114. [PubMed: 22240726]
18. Bosch TA, Dengel DR, Kelly AS, Sinaiko AR, Moran A, Steinberger J. Visceral adipose tissue measured by DXA correlates with measurement by CT and is associated with cardiometabolic risk factors in children. Pediatr Obes 2015;10:172–179. [PubMed: 24990328]
19. Du Bois D, Du Bois EF. A formula to estimate the approximate surface area if height and weight be known. 1916. Nutrition 1989;5:303–311; discussion 312–313. [PubMed: 2520314]
20. Radley D, Gately PJ, Cooke CB, Carroll S, Oldroyd B, Truscott JG. Percentage fat in overweight and obese children: comparison of DXA and air displacement plethysmography. Obes Res 2005;13:75–85. [PubMed: 15761165]
21. Nicholson JC, McDuffie JR, Bonat SH, et al. Estimation of body fatness by air displacement plethysmography in African American and white children. Pediatr Res 2001;50:467–473. [PubMed: 11568289]
22. Eisenkölbl J, Kartasurya M, Widhalm K. Underestimation of percentage fat mass measured by bioelectrical impedance analysis compared to dual energy X-ray absorptiometry method in obese children. Eur J Clin Nutr 2001;55:423. [PubMed: 11423918]
23. Gutin B, Litaker M, Islam S, Manos T, Smith C, Treiber F. Body-composition measurement in 9–11-y-old children by dual-energy X-ray absorptiometry, skinfold-thickness measurements, and bioimpedance analysis. Am J Clin Nutr 1996;63:287–292. [PubMed: 8602582]
24. Lazzer S, Bedogni G, Agosti F, Col AD, Mornati D, Sartorio A. Comparison of dual-energy X-ray absorptiometry, air displacement plethysmography and bioelectrical impedance analysis for the assessment of body composition in severely obese Caucasian children and adolescents. Br J Nutr 2008;100:918–924. [PubMed: 18279552]
25. Hofsteenge GH, Chinapaw MJ, Weijs PJ. Fat-free mass prediction equations for bioelectric impedance analysis compared to dual energy X-ray absorptiometry in obese adolescents: a validation study. BMC Pediatr 2015;15:158. doi:10.1186/s12887-015-0476-7 [PubMed: 26471899]
26. tenHaaf TPG, Memelink RG, Tieland M, Weijs PJM. The difference between body composition analysis measured by air-displacement plethysmography and dual x-ray absorptiometry depends on relative fat mass [ESPEN Abstract OR28]. Clin Nutr 2016:35(suppl 1):S11–S12.
27. Leonard CM, Roza MA, Barr RD, Webber CE. Reproducibility of DXA measurements of bone mineral density and body composition in children. Pediatr Radiol 2009;39:148–154. [PubMed: 19052738]
28. Shepherd JA, Lu Y. A generalized least significant change for individuals measured on different DXA systems. J Clin Densitom 2007;10:249–258. [PubMed: 17616413]
29. Wang J, Gallagher D, Thornton JC, Yu W, Horlick M, Pi-Sunyer FX. Validation of a 3-dimensional photonic scanner for the measurement of body volumes, dimensions, and percentage body fat. Am J Clin Nutr 2006;83:809–816. [PubMed: 16600932]

30. Wells JCK, Treleaven P, Cole TJ. BMI compared with 3-dimensional body shape: the UK National Sizing Survey. Am J Clin Nutr 2007;85:419–425. [PubMed: 17284738]

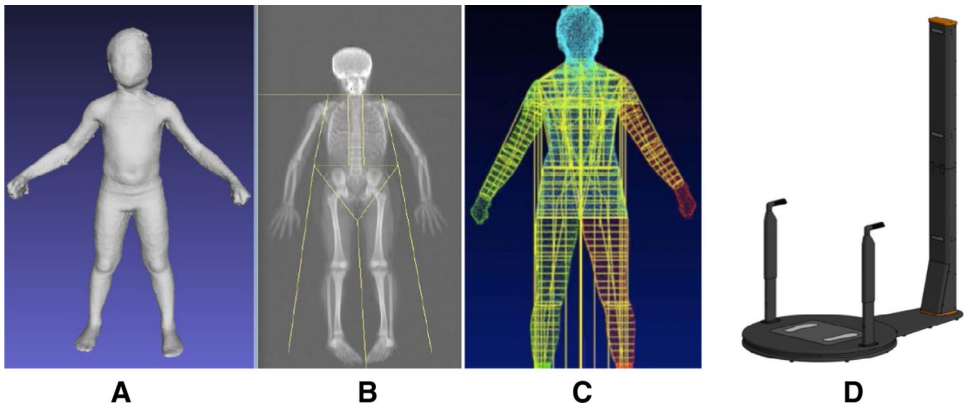

Figure 1.

3DO and DXA scans. (**A**) 3DO image of 6-year-old child on Fit3D ProScanner. (**B**) DXA image of same 6-year-old child. (**C**) Sample image of all 349 lengths and circumferences obtained from Fit3D ProScanner. (**D**) Image of Fit3D ProScanner.

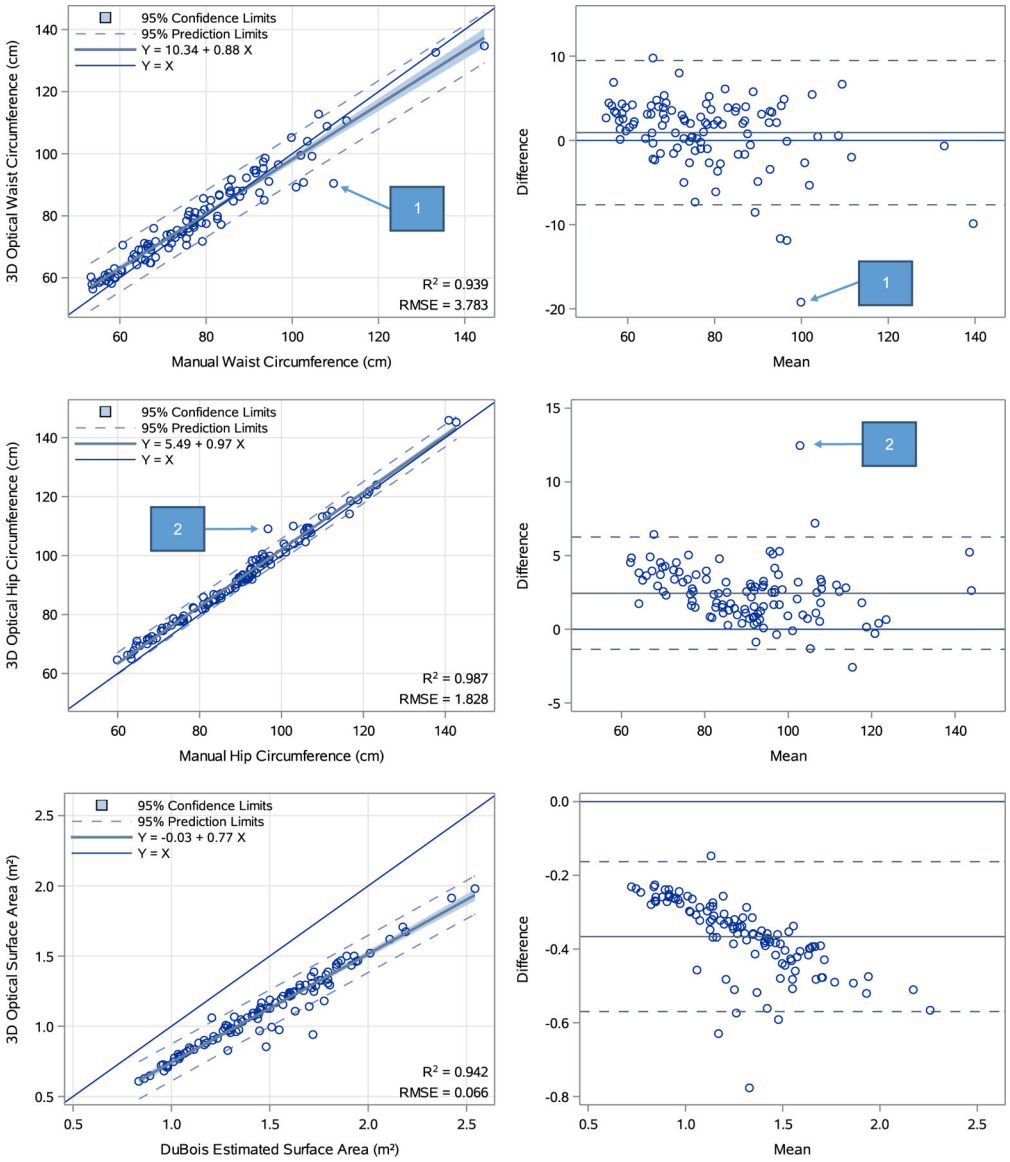

Figure 2.

Regression scatterplots (left) and corresponding Bland-Altman plots (right) for 3DO waist circumferences vs. manual tape measurements, 3DO hip circumference vs. manual tape measurements, and 3DO-estimated surface area vs. DuBois-estimated surface area. Points 1 and 2 are outliers.

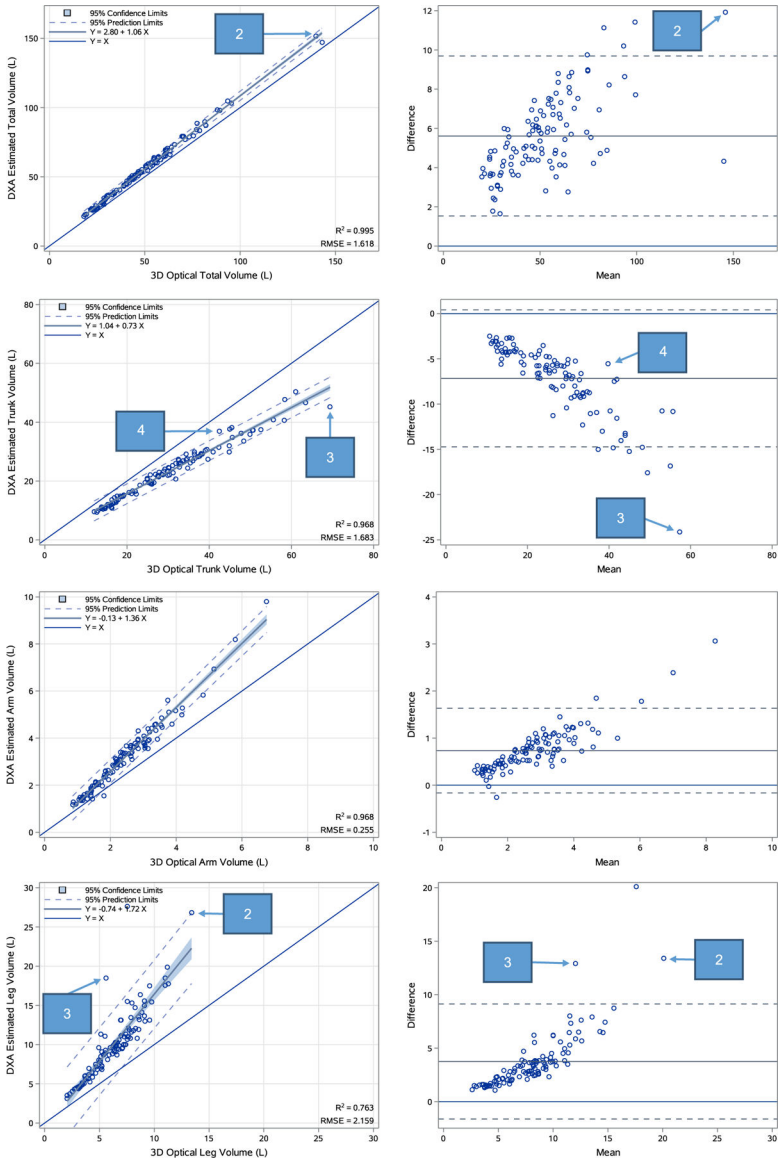

Figure 3.

Regression scatterplots (left) and corresponding Bland-Altman plots (right) for 3DO volume measurements vs. DXA-estimated volumes. Points 2 to 4 are outliers. Total volume, R^2 = 0.99, RMSE = 1.62 L. Trunk volume, R^2 = 0.97, RMSE = 1.68 L. Arm volume, R^2 = 0.97, RMSE = 0.26 L. Leg volume, R^2 = 0.76, RMSE = 2.16 L.

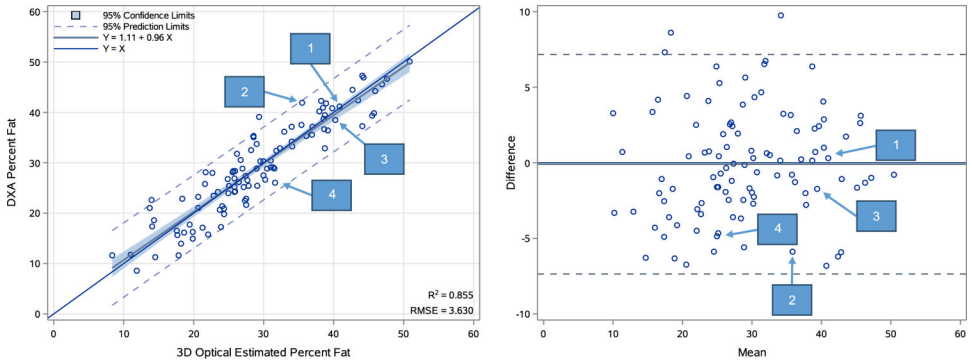

Figure 4.

Regresson scatterplot (left) and corresponding Bland-Altman plot (right) for 3DO body fat percentage vs. DXA body fat percentage. Points 1 to 4 are not outliers.

TABLE 1

Summary characteristics of Shape Up! Kids participants

		Boys					Girls					
Variable	**Unit**	***N***	**Mean**	**SD**	**Min**	**Max**	***N***	**Mean**	**SD**	**Min**	**Max**	***P***
Asian	%	2	1.8				3	2.7				
Non-Hispanic black	%	18	16.1				22	19.6				
Hispanic	%	0	0.0				3	2.7				
Non-Hispanic white	%	26	23.2				38	33.9				
BMI z score < −2	%	1	0.9				0	0.0				
−2 ≤ BMI *z* score < −1	%	1	0.9				5	4.5				
−1 ≤ BMI *z* score < 0	%	15	13.4				12	10.7				
0 ≤ BMI *z* score < 1	%	11	9.8				20	17.9				
1 ≤ BMI *z* score < 2	%	11	9.8				20	17.9				
2 ≤ BMI *z* score	%	7	6.3				9	8.0				
Age	y	46	12.3	3.3	5.3	17.4	66	12.7	3.3	5.8	18.0	0.54
Pubertal stage	Tanner	35	2.8	1.5	1.0	5.0	50	3.3	1.5	1.0	5.0	0.12
Height	cm	46	154.9	18.3	119.9	179.3	66	150.8	14.0	117.8	185.0	0.20
Weight	kg	46	56.2	27.1	22.3	146.8	66	51.7	17.5	21.3	95.6	0.33
Waist (tape)	cm	46	76.1	20.1	53.3	144.5	65	77.2	13.0	53.7	109.6	0.75
Hip (tape)	cm	46	87.7	18.6	60.0	142.7	66	89.4	14.8	59.9	123.3	0.60
Arm (tape)	cm	46	26.2	6.6	17.2	45.5	65	25.7	5.0	16.9	38.8	0.68
Thigh (tape)	cm	45	46.2	13.5	17.8	80.7	64	49.0	8.8	32.7	71.1	0.21
DuBois BSA (formula)	m^2	45	1.51	0.40	0.86	2.54	66	1.45	0.29	0.84	2.19	0.35
Waist circumference (3DO)	cm	44	78.7	18.0	57.9	134.7	62	77.5	12.5	56.3	112.7	0.71
Hip circumference (3DO)	cm	46	90.5	18.3	64.5	146.0	66	91.7	14.3	64.7	123.9	0.72
Arm circumference (3DO)	cm	46	27.3	6.5	18.5	47.9	66	27.1	5.0	19.0	37.7	0.85
Forearm circumference (3DO)	cm	46	25.1	3.7	19.2	34.9	66	23.7	2.7	18.3	29.3	**0.04**
Thigh circumference (3DO)	cm	44	50.6	9.8	35.1	84.0	65	52.7	8.6	34.8	71.9	0.25
Calf circumference (3DO)	cm	46	34.7	5.8	25.9	50.3	66	33.9	4.3	24.7	44.9	0.45
Total surface area (3DO)	m^2	45	1.15	0.31	0.63	1.98	65	1.09	0.23	0.61	1.67	0.29
Torso surface area (3DO)	m^2	46	0.50	0.18	0.29	1.12	66	0.45	0.12	0.26	0.84	0.14

		Boys					Girls					
Variable	**Unit**	***N***	**Mean**	**SD**	**Min**	**Max**	***N***	**Mean**	**SD**	**Min**	**Max**	***P***
Arm left surface area (3DO)	m^2	44	0.11	0.03	0.06	0.17	65	0.10	0.02	0.02	0.15	0.27
Arm right surface area (3DO)	m^2	45	0.11	0.03	0.05	0.17	65	0.10	0.02	0.01	0.15	0.26
Leg left surface area (3DO)	m^2	46	0.22	0.05	0.11	0.35	65	0.22	0.05	0.11	0.32	0.62
Leg right surface area (3DO)	m^2	46	0.22	0.05	0.12	0.34	65	0.22	0.05	0.11	0.32	0.71
Total volume (3DO)	L	46	50.7	26.6	18.5	142.9	66	47.2	17.0	18.1	89.4	0.43
Torso volume (3DO)	L	45	31.8	16.5	12.7	101.5	66	30.1	12.0	12.0	69.4	0.57
Arm left volume (3DO)	L	46	2.5	1.3	0.9	7.0	66	2.3	0.8	0.7	4.4	0.25
Arm right volume (3DO)	L	46	2.5	1.2	0.8	6.5	66	2.2	0.8	0.9	4.2	0.19
Leg left volume (3DO)	L	46	6.1	2.4	2.2	13.7	65	6.3	2.1	2.0	11.3	0.59
Leg right volume (3DO)	L	45	6.0	2.4	1.9	13.1	65	6.2	2.0	2.1	11.3	0.66
Waist-hip ratio (3DO)		44	0.86	0.05	0.76	0.96	62	0.85	0.06	0.73	0.98	0.15
Waist-height ratio (3DO)		43	0.51	0.10	0.41	0.80	62	0.52	0.07	0.42	0.73	0.70
Waist-width ratio (3DO)		44	2.80	0.10	2.52	3.07	62	2.81	0.09	2.66	3.08	0.47

Manual reported circumferences done with tape measurements. Circumferences, surface area, and volume derived from the 3DO scanner. Body composition estimated from 3DO. Bold font indicates $P < 0.05$.

BSA, body surface area; 3DO, three-dimensional optical.

TABLE 2

Precision of circumferences, volumes, surface areas, and body composition measurements

Measure	Variable	%CV	RMSE
Tape measures (cm)	Waist	0.28	0.21
	Hip	0.20	0.18
	Arm	0.46	0.12
	Thigh	0.98	0.47
	DuBois BSA (m^2)	0.08	0.00
3DO circumferences (cm)	Waist	1.37	1.08
	Hip	0.79	0.73
	Arm	2.51	0.69
	Forearm	6.09	1.47
	Thigh	2.59	1.36
	Calf	1.56	0.54
3DO surface areas (m^2)	Total surface area	4.33	0.05
	Torso surface area	8.68	0.04
	Arm surface area	10.73	0.01
	Leg surface area	3.86	0.01
3DO volumes (L)	Total volume	1.57	0.77
	Torso volume	2.43	0.77
	Arm volume	5.46	0.13
	Leg volume	5.33	0.34
3DO ratios	Waist-hip ratio	1.50	0.01
	Waist-height ratio	1.82	0.01
	Waist-width ratio	1.29	0.04
3DO-estimated body composition (kg)	Total fat mass	3.30	0.53
	Total fat-free mass	1.34	0.53
	Total percent fat (%)		1.20
	Fat mass index (kg/m^2)	3.57	0.24
	Fat-free mass index (kg/m^2)	1.46	0.24
	Visceral fat mass	6.07	0.04

Measure	Variable	%CV	RMSE
	Trunk fat	5.84	0.40
	Trunk fat-free	1.69	0.31
	Arms fat	4.29	0.05
	Arms fat-free	2.05	0.04
	Legs fat	5.56	0.20
	Legs fat-free	1.90	0.12

Table shows precision between test-retest of 3DO measurements.

3DO, three-dimensional optical; %CV, coefficient of variation; DuBois BSA, DuBois body surface area; RMSE, root mean square error.

TABLE 3

Derived fat mass, fat-free mass, and percent fat prediction equations from 3DO measurements

Outcome	Parameter	Estimate	*P*	R^2	RMSE
Total fat mass	Intercept	−8.84	0.06	0.96	1.83
	Male	2.95	0.06		
	Age	−0.43	**0.0002**		
	Male * age	−0.36	**0.007**		
	Waist circumference	0.16	**0.002**		
	Hip circumference	0.23	**0.002**		
	Arm circumference	0.72	**<10^{-4}**		
	Forearm circumference	−0.92	**<10^{-4}**		
	Torso surface area	−38.98	**<10^{-4}**		
	Torso volume	0.61	**<10^{-4}**		
Total fat-free mass	Mass − P fat mass			0.98	1.83
Total percent fat	P fat mass ÷ mass			0.83	3.87
Fat mass index	P fat mass ÷ height^2			0.96	0.84
Fat-free mass index	(Mass − P fat mass) ÷ height^2			0.91	0.80
Visceral body fat	Intercept	−3.64	**<10^{-4}**	0.92	0.15
	Male * age	−0.01	**0.001**		
	Waist circumference	0.02	**<10^{-4}**		
	Waist-height ratio	1.63	**<10^{-4}**		
	Waist-width ratio	0.58	**0.003**		
Trunk fat	Intercept	−0.18	0.93	0.94	1.04
	Male * age	−0.07	**0.002**		
	Waist circumference	0.13	**<10^{-4}**		
	Arm circumference	0.54	**<10^{-4}**		
	Forearm circumference	−0.68	**<10^{-4}**		
	Torso surface area	−21.25	**0.0001**		
	Arm surface area	−26.11	**0.03**		
	Torso volume	0.35	**<10^{-4}**		

Obesity (Silver Spring). Author manuscript; available in PMC 2021 February 15.

Outcome	Parameter	Estimate	*P*	R^2	RMSE
Trunk fat-free	Intercept	4.29	0.08	0.96	1.26
	Age	0.40	**<10^{-4}**		
	Male*age	0.33	**0.0003**		
	Male*circumference	−0.03	**0.02**		
	Thigh circumference	−0.31	**<10^{-4}**		
	Total surface area	9.73	**0.002**		
	Total volume	0.17	**<10^{-4}**		
	Leg volume	0.69	**0.02**		
Arm fat	Intercept	−2.13	**<10^{-4}**	0.92	0.18
	Age	−0.02	**0.02**		
	Male*age	−0.06	**<10^{-4}**		
	Waist circumference	0.02	**<10^{-4}**		
	Arm circumference	0.06	**<10^{-4}**		
	Male*thigh circumference	0.01	**0.0001**		
Arm fat-free	Intercept	−0.22	**0.24**	0.92	0.24
	Male*age	0.12	**<10^{-4}**		
	Male*waist circumference	−0.04	**<10^{-4}**		
	Thigh circumference	−0.02	**0.006**		
	Total surface area	2.89	**<10^{-4}**		
	Male*arm volume	0.38	**0.0003**		
	Male*waist-height ratio	2.71	**0.01**		
Leg fat	Intercept	−7.27	**<10^{-4}**	0.92	0.58
	Age	−0.20	**<10^{-4}**		
	Hips circumference	0.16	**<10^{-4}**		
	Arm surface area	−14.11	**0.002**		
Leg fat-free	Intercept	0.55	**0.59**	0.94	0.66
	Male*age	0.17	**<10^{-4}**		
	Waist circumference	−0.05	**0.0003**		
	Total surface area	8.11	**0.0003**		

Outcome	Parameter	Estimate	*P*	R^2	RMSE
	Arm surface area	−21.00	**0.10**		
	Total volume	0.05	**0.01**		
	Male * waist-height ratio	−2.60	**0.0005**		

Predicted whole-body and regional body composition measurements derived from 3DO measurements and validated against whole-body DXA results. Body composition equations are listed. Parameters used for each model are listed. Bold font indicates $P < 0.05$.

*, interaction term; P fat mass, predicted total fat mass; RMSE, root mean square error.

Obesity (Silver Spring). Author manuscript; available in PMC 2021 February 15.

TABLE 4

Training vs. test results

	Training					Test				
Outcome	***N***	***R*²**	**LCL**	**UCL**	**RMSE**	***N***	***R*²**	**LCL**	**UCL**	**RMSE**
Total fat mass	104	0.96	0.94	0.97	1.83	47	0.93	0.89	0.95	2.60
Total fat-free mass	104	0.98	0.97	0.98	1.83	47	0.95	0.92	0.96	2.80
Total percent fat	104	0.83	0.77	0.87	3.87	47	0.70	0.53	0.79	4.71
Fat mass index	105	0.96	0.94	0.96	0.84	47	0.90	0.84	0.93	1.10
Fat-free mass index	104	0.91	0.88	0.93	0.80	47	0.81	0.69	0.86	1.24
Visceral body fat	104	0.92	0.90	0.94	0.15	47	0.89	0.82	0.92	0.19
Trunk fat	103	0.94	0.92	0.95	1.04	48	0.92	0.87	0.95	1.51
Trunk fat-free	102	0.96	0.95	0.97	1.26	49	0.95	0.92	0.96	1.48
Arm fat	103	0.92	0.89	0.94	0.18	49	0.90	0.84	0.93	0.22
Arm fat-free	101	0.92	0.89	0.93	0.24	47	0.89	0.82	0.92	0.29
Leg fat	111	0.92	0.89	0.94	0.58	48	0.86	0.77	0.90	0.64
Leg fat-free	103	0.94	0.91	0.95	0.66	48	0.95	0.91	0.96	0.58

Participants in test group were not used to build training model. Test group validated equations derived from training group.

LCL, lower control limit; RMSE, root mean square error; UCL, upper control limit.

Obesity (Silver Spring). Author manuscript; available in PMC 2021 February 15.